

Stellar Sources for Heavy r -Process Nuclei

Y.-Z. Qian¹ and G. J. Wasserburg²

ABSTRACT

The stellar sites and the complete mechanism of r -process nucleosynthesis are still unresolved issues. From consideration of the observed abundances in metal-poor stars, it is proposed that the production of the heavy r -process nuclei (r -nuclei with mass numbers $A > 130$) is not related to the production of the Fe group elements or of the elements with lower atomic numbers: Na, Mg, Al, Si, Ca, Sc, and Ti. This requires that the production of the heavy r -nuclei not occur in supernovae with extended shell structure, but be associated with either bare neutron stars or Type II supernovae (SNe II) in the mass range $8 M_{\odot} < M < 10 M_{\odot}$. From the observations of stars with $[\text{Fe}/\text{H}] \sim -3$ but with high abundances of r -elements, it is clear that these r -process enrichments cannot represent the composition of the interstellar medium from which the stars were formed, but must represent very local contamination from binary companions. Further evidence for very high enrichments of s -process elements in metal-poor stars also requires binary systems for explanation. We propose that the accretion-induced collapse (AIC) of a white dwarf into a neutron star in a binary system may be associated with the production of the heavy r -nuclei and may provide occasional coupling of high r -process and high s -process enrichments in the envelopes of low-mass stars with low $[\text{Fe}/\text{H}]$. If we assume that the bulk of the heavy r -nuclei are produced in AIC events, then these events would have produced $\sim 1.6 \times 10^9$ neutron stars in the Galaxy. A much larger number of white dwarf binaries would have resulted from the evolution of other binary systems. The AIC scenario removes the assignment in our earlier model that SNe II provide the bulk of the heavy r -nuclei and relegates r -process production in SNe II to the light r -nuclei with $A \lesssim 130$. This new assignment removes the requirement in our earlier model that most SNe II produce no Fe and gives Fe yields that are in accord with the observed values for most SNe II.

¹School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455; qian@physics.umn.edu.

²The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125; isotopes@gps.caltech.edu.

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1. Introduction

In this paper we try to establish the intrinsic characteristics of the stellar sources for the heavy r -process nuclei (r -nuclei with mass numbers $A > 130$ corresponding to the elements Ba and above) using aspects of a phenomenological model presented earlier (Wasserburg & Qian 2000; Qian & Wasserburg 2001b, 2002). The bulk of the light r -nuclei (with $A \lesssim 130$) appear to have different sources from those for the heavy r -nuclei (Wasserburg, Busso, & Gallino 1996) and are not extensively discussed here. From the observational data on metal-poor (i.e., low $[\text{Fe}/\text{H}]$) stars, we will show that the heavy r -nuclei are produced with only some coproduction of the light r -elements such as Sr, Y, and Zr, but without any coproduction of the elements from Na to Zn (including Fe). We argue that supernovae with extended shell structure cannot be the source for the heavy r -nuclei. Instead, these nuclei must be produced during the formation of an essentially bare neutron star. Such a state may result from a low-mass ($\sim 8\text{--}10 M_{\odot}$) Type II supernova (SN II) or from the accretion-induced collapse (AIC) of a white dwarf into a neutron star in a binary system. The observational basis that establishes the distinctive characteristics of the stellar sources for the heavy r -nuclei is discussed in §2. In §3 we discuss the requirement of an essentially bare neutron star for the production of the heavy r -nuclei and the proposed role of AIC events. The special nature of both r -process and s -process enrichments in binary systems with AIC is discussed in §4. In §5 we explore some of the consequences for our earlier model and other implications that follow if AIC events are a source for the heavy r -nuclei.

2. Observational Basis

Elemental abundances in halo stars of low metallicities have provided fundamental data for understanding nucleosynthesis and chemical evolution of the Galaxy. The observations (McWilliams et al. 1995; Ryan, Norris, & Beers 1996; Burris et al. 2000; Westin et al. 2000; Sneden et al. 2000; Norris, Ryan, & Beers 2001) led us to propose earlier that there was a major transition at $[\text{Fe}/\text{H}] \sim -3$ in the production of heavy elements. The Fe production at $[\text{Fe}/\text{H}] < -3$ was dominated by very massive ($\gtrsim 100 M_{\odot}$) stars (VMSs). It was proposed that the VMS activities ceased and major formation of normal stars (with masses $M \sim 1\text{--}$

$60 M_{\odot}$) took over when a critical metallicity corresponding to $[\text{Fe}/\text{H}] \sim -3$ was reached in the interstellar medium (ISM). This is in accord with the recent study by Bromm et al. (2001), which indicates that substantial formation of a normal stellar population could only occur when a metallicity substantially above 5×10^{-4} times the solar value was achieved in the ISM to provide sufficient cooling for the collapse and fragmentation of gas clouds. The subsequent Fe production at $-3 < [\text{Fe}/\text{H}] < -1$ was then considered to be dominated by SNe II. The production of the heavy r -elements relative to Fe was very low prior to the achievement of $[\text{Fe}/\text{H}] \sim -3$ in the ISM, but increased sharply at $[\text{Fe}/\text{H}] \sim -3$ and subsequently approached a well-defined trend for normal stages of Galactic evolution (Wasserburg & Qian 2000; Qian & Wasserburg 2001b, 2002). This behavior is shown for Eu (a predominantly r -process element in the solar system) in Figure 1a where the available data on $\log \epsilon(\text{Eu})$ are plotted versus $[\text{Fe}/\text{H}]$ ³. It can be seen that for $[\text{Fe}/\text{H}] < -2.4$ there is a very wide scatter in $\log \epsilon(\text{Eu})$ while for higher values of $[\text{Fe}/\text{H}]$ $\log \epsilon(\text{Eu})$ follows $[\text{Fe}/\text{H}]$ in a more regular trend. This trend is indicated by the solid line segment of unit slope in Figure 1a and reflects a constant Eu/Fe ratio for the net production by all stellar sources. The results for Eu are similar to those for Ba as shown in Figure 1b. The transition at $[\text{Fe}/\text{H}] \sim -3$ is prominently demonstrated for Ba by the contrast between the data at $[\text{Fe}/\text{H}] < -3$ and those at $[\text{Fe}/\text{H}] > -3$. Note that this transition reflects the changes in the relative production rates of the heavy r -elements with respect to Fe, and therefore, can be used to identify the nucleosynthetic contributions to the ISM from the sources for the heavy r -elements relative to those from the sources for Fe. For example, the transition for Ba corresponds to an increase by a factor of 10 (solid curve in Fig. 1b) to 20 (dot-dashed curve in Fig. 1b) in the relative production of Ba with respect to Fe from $[\text{Fe}/\text{H}] < -3$ to $[\text{Fe}/\text{H}] > -3$ (Qian & Wasserburg 2002). However, the transition at $[\text{Fe}/\text{H}] \sim -3$ by itself cannot identify the relative populations of the different stellar types.

To elucidate the nature of the sources for the heavy r -elements, we exhibit in Figure 2 the available data on HD 115444, HD 122563 (Westin et al. 2000), and CS 31082–001 (Hill et al. 2002) with $[\text{Fe}/\text{H}] = -2.99$, -2.74 , and -2.9 , respectively, which show clear evidence for varying degrees of r -process enrichment within a narrow range of $[\text{Fe}/\text{H}]$. We note that the data (not shown) on CS 22892–052 with $[\text{Fe}/\text{H}] = -3.1$ (McWilliam et al. 1995; Sneden et al. 2000) are very close to those on CS 31082–001. We also note that high Th abundances were found in CS 22892–052 and HD 115444 while high Th and U abundances were found in CS 31082–001. It can be seen from Figure 2a that the abundances of the elements from Na to Zn (including Fe) in the three stars shown there are all rather constant

³Standard spectroscopic notation is used here: $\log \epsilon(\text{E}) \equiv \log(\text{E}/\text{H}) + 12$, where (E/H) is the abundance ratio of element E to hydrogen in a star, and $[\text{Fe}/\text{H}] \equiv \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_{\odot}$.

with a typical range of ~ 0.3 dex in $\log \epsilon$. This is in sharp contrast to the wide range of ~ 2 dex in $\log \epsilon$ for the heavy r -elements (Ba and above) as shown in Figure 2b for the same stars. Figure 2b also shows that the relative abundances of the heavy r -elements in each star can be described remarkably well by the solar r -process abundance pattern (solar r -pattern). Indeed, extensive studies (e.g., Sneden et al. 1996; Johnson & Bolte 2001) found that the heavy r -elements in a number of metal-poor stars often closely follow the solar r -pattern while having widely varying absolute abundances.

It follows from Figure 2 that the sources for the heavy r -nuclei are not connected with the production of the elements from Na to Zn, which include not only the Fe group but also the so-called “ α -elements” Mg, Si, Ca, and Ti. This observation was discussed in our earlier study (Qian & Wasserburg 2002) of the nucleosynthetic yields which we attributed to VMSs and two hypothesized types of SNe II [SNe II(H) and SNe II(L)]. In particular, the abundances of the elements from Na to Zn at $[\text{Fe}/\text{H}] \sim -3$ were considered to represent a prompt inventory of the elements dominantly produced by VMSs. The prompt inventory of the light r -elements Sr, Y, and Zr is also significant (Qian & Wasserburg 2001b). This can be seen from the data on HD 115444 and HD 122563 shown in Figure 2b. These two stars have very different abundances of the heavy r -elements but essentially the same abundances of Sr, Y, and Zr, which are dominated by the prompt inventory of these elements. Compared with HD 115444 and HD 122563, CS 31082–001 have much higher abundances of the heavy r -elements and significantly higher abundances of Sr, Y, and Zr (see Fig. 2b). This indicates that the sources for the heavy r -nuclei also produce some light r -nuclei and such contributions overwhelm the prompt inventory of Sr, Y, and Zr in CS 31082–001. The data on CS 31082–001 (see Fig. 2b) and CS 22892–052 (Sneden et al. 2000) show that the light r -elements produced by the sources for the heavy r -nuclei in these two stars also include Nb, Ru, Rh, Pd, Ag, and Cd. However, the sources for the bulk of the light r -nuclei appear to be different from those for the heavy r -nuclei as first argued by Wasserburg et al. (1996) based on the inventory of ^{182}Hf and ^{129}I in the early solar system. This was supported by the data on CS 22892–052 (Sneden et al. 2000), CS 31082–001 (Hill et al. 2002), BD +17°3248 (Cowan et al. 2002), and several other metal-poor stars (Johnson & Bolte 2002b), which showed that the light r -elements such as Ag in these stars are clearly deficient relative to the solar r -pattern translated to pass through the Eu data. The production of the light r -elements appears to be associated with that of Fe. This was studied in some detail in Qian & Wasserburg (2001b) but will not be extensively discussed here.

The range in $\log \epsilon$ for Eu and Ba in many halo stars with $[\text{Fe}/\text{H}] \sim -3$ shown in Figure 1 and the range in $\log \epsilon$ for the pure heavy r -elements in three such stars shown in Figure 2 require special attention. If we consider that the solar r -process abundances represent the Galactic average at the time of solar system formation (SSF), and that the absolute

yield Y_E/H of element (or nuclide) E per H atom in a standard reference mass of ISM which will mix with the nucleosynthetic products is constant for every event producing the heavy r -nuclei, it follows (see Appendix A) that

$$(E/H)_{\odot,r} = fT_{\odot}(Y_E/H) = n_{\odot}(Y_E/H), \quad (1)$$

where $(E/H)_{\odot,r}$ is the solar r -process abundance ratio of E to hydrogen and f is the frequency for replenishing the standard reference mass of ISM with newly-synthesized material by the events producing the heavy r -nuclei. The term $n_{\odot} = fT_{\odot}$ is the number of such events per standard reference mass of ISM over the period $T_{\odot} \sim 10^{10}$ yr prior to SSF. Based on the abundance of ^{182}Hf (with a mean lifetime of 1.3×10^7 yr) in the early solar system, f was estimated to be $\sim (10^7 \text{ yr})^{-1}$ (Wasserburg et al. 1996; Qian & Wasserburg 2000). This gives $n_{\odot} \sim 10^3$. For a metal-poor star formed from the ISM in the early Galaxy, the number n of the events contributing to the abundance of E in the star is

$$n = n_{\odot} \frac{(E/H)}{(E/H)_{\odot,r}}, \quad (2)$$

where (E/H) is the number abundance ratio of E to hydrogen in the star.

For the three stars with $[\text{Fe}/H] \sim -3$ shown in Figure 2, their enrichments of heavy r -elements correspond to $n \sim 1$ –50. While the abundances corresponding to $n \sim 1$ –10 for e.g., Eu , can be reasonably attributed to the enrichment of an average ISM at $[\text{Fe}/H] \sim -3$ by the events producing the heavy r -nuclei, it is rather problematic to consider that $n \sim 50$ such events could have occurred in an average ISM without any other events also occurring to change the Fe abundance. As argued earlier by us (Qian & Wasserburg 2001a), the high r -process enrichments in stars with very low $[\text{Fe}/H]$ such as CS 22892–052 and CS 31082–001 (Eu and Ba data shown as filled diamonds and filled circles, respectively, in Fig. 1) most plausibly resulted from surface contamination by being a low-mass binary companion to the stellar source for the heavy r -nuclei. There is some indication that CS 22892–052 might be in a binary (Preston & Sneden 2001).

A special case of high Eu enrichment at low $[\text{Fe}/H]$ was discovered recently by J. Cohen and N. Christlieb, who found $\log \epsilon(\text{Eu}) = 0.17$ corresponding to $n \sim 460$ for HE 2148–1247 with $[\text{Fe}/H] = -2.3$ (Cohen et al. 2003). The data point (open diamond in Fig. 1a) for this star lies far above the trend for the evolution of Eu relative to Fe at $[\text{Fe}/H] > -2.4$. The result for Ba is similar (see Fig. 1b). Upon being informed of the initial discovery and prior to the detection of Pb in this star, we attempted to predict the abundances of all the other elements from only the preliminary data on Eu and Fe using our earlier model (Qian & Wasserburg 2001b, 2002), which assumes no s -process contributions. These predictions are shown along with the final data in Figure 3a. It can be seen that in consideration of the

observational errors, there is good agreement between the predictions and the data for most of the elements. This is the case especially for the elements from Mg to Ni, the predicted abundances of which have significant contributions from the prompt inventory. However, there is a serious discrepancy for the elements Ba, La, Ce, Pr, and Nd as highlighted in Figure 3b. This discrepancy and the detection of high Pb abundance in HE 2148–1247 unambiguously demonstrate the presence of high *s*-process enrichments in this star [the Pb in this star cannot be plausibly attributed to the decay of the actinides produced by the *r*-process as the observed value of $\log \epsilon(\text{Pb}) = 2.8$ far exceeds $\log \epsilon(\text{Th}) = -0.5$]. On the other hand, the Ba/Eu ratio in this star is ~ 6 times smaller than that for the main *s*-component of the solar abundances (Arlandini et al. 1999). We cannot construct an *s*-process scenario that could decrease the Ba/Eu ratio greatly below the value for the solar main *s*-component. This and the tentatively inferred Th abundance would imply a mixture of high *s*-process and high *r*-process enrichments in HE 2148–1247, the explanation of which requires a new approach and is discussed here and in Cohen et al. (2003).

It was well recognized that the high *s*-process enrichments in metal-poor stars are associated with mass transfer from their previous asymptotic giant branch (AGB) companions in binaries. Four such stars with confirmed binary membership are LP 625–44 with $[\text{Fe}/\text{H}] = -2.7$ (Aoki et al. 2000), CS 22948–027 with $[\text{Fe}/\text{H}] = -2.5$ (Hill et al. 2000; Preston & Sneden 2001), CS 22942–019 with $[\text{Fe}/\text{H}] = -2.7$ (Preston & Sneden 2001), and HE 0024–2523 with $[\text{Fe}/\text{H}] = -2.7$ (Lucatello et al. 2003). There is also evidence for HE 2148–1247 being in a binary (Cohen et al. 2003).

From the above discussion, it is apparent that: (1) the production of the heavy *r*-nuclei is decoupled from the production of the elements from Na to Zn (including the “ α -elements” and the Fe group); (2) surface contamination of a low-mass binary companion by the stellar source for the heavy *r*-nuclei is a relatively common occurrence; (3) surface contamination with *s*-process products is a fairly common occurrence; and (4) there seems to be a coupling of high *s*-process and high *r*-process enrichments in at least one metal-poor star.

3. Stellar Sources for Heavy *r*-Nuclei

The fundamental criterion for an astrophysical environment to be the site for *r*-process nucleosynthesis is the capability of providing a large neutron abundance on a short timescale. Two major candidate environments are the neutrino-driven wind from new-born neutron stars (e.g., Woosley & Baron 1992) and the ejecta from neutron star mergers (e.g., Freiburghaus, Rosswog, & Thielemann 1999). In the neutron star merger model, the material undergoing nucleosynthesis is ejected from a bare old neutron star that is disrupted during the merging

with another neutron star or a black hole. Regardless of the possibility of an r -process, production of the elements from Na to Zn would not be expected to occur in this material. Thus, if neutron star mergers are a source for the heavy r -nuclei, the observational requirement that the production of these nuclei not be related to the production of the elements from Na to Zn is satisfied. However, due to the rarity of neutron star mergers, very large yields per event are required to account for the total r -process abundances in the present Galaxy if these events are the major source for the r -nuclei. The required large yields appear to be in conflict with the level of r -process enrichment observed in metal-poor stars (Qian 2000). While the possibility of neutron star mergers being the r -process site deserves further investigation, here we focus on the neutrino-driven wind from new-born neutron stars as the likely source for the heavy r -nuclei.

A neutron star can be formed from the collapse of (1) an Fe core of stars with $M > 10 M_\odot$, (2) an O-Ne-Mg core of stars with $M \sim 8\text{--}10 M_\odot$, and (3) a white dwarf which has been accreting material from its low-mass companion in a binary system. The surface layers of a new-born neutron star are heated by an enormous flux of neutrinos through the reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$, which results in a neutrino-driven wind (Duncan, Shapiro, & Wasserman 1986). This wind was studied as a possible r -process site but with very uncertain results (e.g., Woosley & Baron 1992; Meyer et al. 1992; Takahashi, Witt, & Janka 1994; Woosley et al. 1994). Independent of these theoretical uncertainties, the observational requirement that the production of the heavy r -nuclei be decoupled from the production of the elements from Na to Zn (including the “ α -elements” and the Fe group) strongly constrains the possible association of the above neutron star formation scenarios with the sources for the heavy r -nuclei. Stars with $M > 10 M_\odot$ possess extensive shells surrounding the Fe core. These shells contain the elements from Na to the Fe group when they are ejected in the SN II explosion of the star subsequent to the collapse of the Fe core (e.g., Woosley & Weaver 1995; Thielemann, Nomoto, & Hashimoto 1996). Therefore, SNe II from stars with $M > 10 M_\odot$ cannot be associated with the source for the heavy r -nuclei that were observed in the stars shown in Figure 2. Stars with $M \sim 8\text{--}10 M_\odot$ have insignificant shells surrounding the O-Ne-Mg core (Nomoto 1984). The SN II explosion resulting from the core collapse of such stars produces essentially no elements from Na to Zn (Nomoto 1987), and therefore, can be associated with the source for the heavy r -nuclei as argued earlier by us (Qian & Wasserburg 2002; see also Wheeler, Cowan, & Hillebrandt 1998). The accretion-induced collapse (AIC) of a white dwarf produces a bare neutron star which ejects material only through the neutrino-driven wind. Thus, the AIC events can also be a source for the heavy r -nuclei.

The AIC of a white dwarf was initially proposed to explain the origin of neutron stars with low-mass binary companions (see Canal, Isern, & Labay 1990 for a review). The white

dwarf in an AIC event may be of C-O composition for a progenitor with $1 M_{\odot} < M < 8 M_{\odot}$ or of O-Ne-Mg composition for a progenitor with $M \sim 8\text{--}12 M_{\odot}$. [Due to tidal mass loss, the progenitor mass range for the formation of an O-Ne-Mg core in binary systems is wider than the range $M \sim 8\text{--}10 M_{\odot}$ for single stars (Nomoto & Kondo 1991).] Nomoto & Kondo (1991) showed that in both cases a broad range of mass accretion rates would lead to AIC. Studies of nucleosynthesis in the neutrino-driven wind associated with AIC events (Woosley & Baron 1992; Fryer et al. 1999) found no r -processing. Instead, these studies showed that elements such as Sr, Y, and Zr are produced profusely by AIC events. This was used to argue that these events should be very rare. Consequently, AIC events have not been considered as a serious candidate for the r -process site. However, the conditions in the neutrino-driven wind are sensitive to many uncertainties in the neutrino and neutron star physics (e.g., Qian & Woosley 1996). In the arguments presented below, we will assume that the conditions in the wind associated with AIC events are suitable for producing the heavy r -nuclei. We hope that the observational evidence discussed here would stimulate and possibly guide further theoretical studies of these events in connection with r -process nucleosynthesis.

4. AIC Events and Chemical Enrichments in Binary Systems

As argued above, if the AIC events are a source for the heavy r -nuclei, then the production of these nuclei is automatically decoupled from the production of the elements from Na to Zn. In addition, as these events occur in binary systems, the ejecta from such events would naturally lead to contamination of the low-mass companion’s surface with heavy r -elements. As material is ejected through the neutrino-driven wind with only a small total mass loss in the AIC events, ablation of the companion may be insignificant compared with the case of SNe II. Further, the AIC model for the production of the heavy r -nuclei requires that there be a coupling of r -process and s -process enrichments in binary systems.

In general, a star evolves through the AGB phase prior to becoming a white dwarf. This evolution results in production of neutrons, the capture of which by the Fe seeds gives rise to the s -process. Depending on the distribution of neutron fluence or the ratio of neutrons to the Fe seeds, low-metallicity AGB stars may predominantly produce Pb (e.g., Van Eck et al. 2001) as predicted by Gallino et al. (1998) or produce an s -process pattern similar to the main s -component of the solar abundances (e.g., Aoki et al. 2000), or produce some superposition of high Pb enrichment and the main solar s -component (e.g., Johnson & Bolte 2002a; Cohen et al. 2003). In any case, the s -process products along with the other elements in the envelope of the AGB star may be dumped onto the surface of a low-mass companion via mass transfer in a binary. If the white dwarf left behind by the AGB star subsequently

accretes mass from the companion and undergoes AIC, the surface of the companion will be enriched again, but this time with heavy r -elements. It is also plausible that the ratio of neutrons to the Fe seeds in some AGB stars would be too low for any significant s -processing to occur⁴ (the problem of s -processing at low metallicities is now attracting considerable attention). Thus, the low-mass star in a binary may have a surface composition ranging from predominantly r -process [e.g., possibly CS 22892–052 (Snedden et al. 2000; Preston & Sneden 2001)] to predominantly s -process [e.g., LP 625–44 (Aoki et al. 2000)] in origin. The elements C, N, and O will then reflect the normal stellar processing in the low-mass star (e.g., Fujimoto, Ikeda, & Iben 2000) and additions from the standard evolution of the originally more massive AGB companion. It may be rather common to find metal-poor stars with high surface enrichments of both s -process and r -process elements. We note that a number of metal-poor stars were observed with high s -process enrichments (e.g., Hill et al. 2000; Aoki et al. 2000; Johnson & Bolte 2002a; Lucatello et al. 2003). Unfortunately, the element Th, which is unique to the r -process, is either not targeted for observations or is difficult to detect for these stars. We know of only one star, HE 2148–1247, the surface composition of which reflects a superposition of s -process and r -process products possibly including Th (Cohen et al. 2003).

Without Th detection, significant r -process enrichments may still be identified based on the observed abundance pattern of the elements Ba and above. This is because for these elements, the patterns produced by the s -process are drastically different from the pattern produced by the r -process. A convenient measure to characterize this difference is the Ba/Eu ratio. As mentioned earlier, observations showed that the abundances of the heavy r -elements in a number of metal-poor stars closely follow the solar r -pattern. This suggests that the Ba/Eu ratio for the events producing the heavy r -nuclei is close to the solar r -process value $(\text{Ba}/\text{Eu})_{\odot,r} \approx 9$ (Arlandini et al. 1999). By contrast, the Ba/Eu ratio for the solar main s -component is $(\text{Ba}/\text{Eu})_{\odot,s} \approx 650$ (Arlandini et al. 1999). Due to the variations in the ratio of neutrons to the Fe seeds, the s -process in low-metallicity AGB stars will in general produce different Ba/Eu ratios from $(\text{Ba}/\text{Eu})_{\odot,s}$. The metallicity dependence of the s -process production pattern was demonstrated by the data (Van Eck et al. 2001) on three metal-poor stars, the s -process abundances of which do not follow the solar main s -component but are characterized by predominant Pb enrichments as predicted by Gallino et al. (1998). Models that were in good agreement with the data on Zr, La, Ce, Pr, Nd, Sm, and Pb in these stars gave the s -process ratios $(\text{Ba}/\text{Eu})_s \approx 300$ for $[\text{Fe}/\text{H}] \approx -1.7$

⁴In fact, the more massive star of a close binary system may not go through the AGB phase (e.g., Iben 1985), and therefore, no s -processing would occur in the star. However, this star still produces a white dwarf, the AIC of which can then provide pure r -process enrichments to the low-mass companion.

and $(\text{Ba}/\text{Eu})_s \approx 170$ for $[\text{Fe}/\text{H}] \approx -2.5$ (Van Eck et al. 2001). Thus, it appears that the s -process always produces $(\text{Ba}/\text{Eu})_s \gg (\text{Ba}/\text{Eu})_{\odot,r}$.

The Ba/Eu ratio in a star is given by

$$\left(\frac{\text{Ba}}{\text{Eu}}\right) = \frac{(\text{Ba}/\text{Eu})_s}{1 - \beta_r(\text{Ba}) + [(\text{Ba}/\text{Eu})_s/(\text{Ba}/\text{Eu})_{\odot,r}]\beta_r(\text{Ba})}, \quad (3)$$

where $\beta_r(\text{Ba})$ is the fraction of Ba contributed by the r -process. The Ba/Eu ratio in the star can also be given by

$$(\text{Ba}/\text{Eu}) = (\text{Ba}/\text{Eu})_s \beta_s(\text{Eu}) + (\text{Ba}/\text{Eu})_{\odot,r} [1 - \beta_s(\text{Eu})], \quad (4)$$

where $\beta_s(\text{Eu})$ is the fraction of Eu contributed by the s -process. A general question is when the r -process and the s -process contributions can be identified for a star with a mixture of such contributions. From Equation (3), the r -process contributions to the star can be well recognized by the abundance pattern for $\beta_r(\text{Ba}) \gg (\text{Ba}/\text{Eu})_{\odot,r}/(\text{Ba}/\text{Eu})_s$. From Equation (4), the s -process contributions to the star can be identified for $\beta_s(\text{Eu}) \gg (\text{Ba}/\text{Eu})_{\odot,r}/(\text{Ba}/\text{Eu})_s$. This is illustrated in Figure 4 by considering mixtures of the solar r -pattern and the solar main s -component. For such mixtures, the reference value to be compared with $\beta_r(\text{Ba})$ and $\beta_s(\text{Eu})$ is $(\text{Ba}/\text{Eu})_{\odot,r}/(\text{Ba}/\text{Eu})_{\odot,s} \approx 0.014$. The dot-dashed curve in Figure 4a represents a mixture in which the Ba receives equal contributions from the r -process and the s -process [$\beta_r(\text{Ba}) = 0.5$]. It can be seen that this curve closely follows the solar r -pattern (thick solid curve) and the s -process contributions are essentially obscured. This can be understood as only $\approx 1.4\%$ of the Eu [$\beta_s(\text{Eu}) \approx 0.014$] is contributed by the s -process. It follows that if $\gtrsim 50\%$ of the Ba in a star is from the r -process, then the abundances of all the elements above Ba will exhibit the solar r -pattern. The case of $\beta_r(\text{Ba}) = 0.5$ corresponding to $\beta_s(\text{Eu}) \approx 0.014$ is also shown in Figure 4b. For comparison, the thin solid curve in Figure 4b represents a mixture in which the Eu receives equal contributions from the r -process and the s -process [$\beta_s(\text{Eu}) = 0.5$]. It can be seen that this curve closely follows the solar main s -component (dashed curve). We emphasize that if $\gtrsim 50\%$ of the Eu in a star is from the s -process, the overall abundance pattern will not be easily distinguishable from an s -pattern. The identification of the r -process and the s -process contributions is also complicated by the observational errors ($\sim \pm 0.1$ dex in $\log \epsilon$) and by the possible variations of $(\text{Ba}/\text{Eu})_s$. In very uncertain cases, the r -process contributions can only be identified by the data on Ir, Th, and U, which receive much less or no contribution from the s -process compared with Eu.

The observed abundance pattern of the elements from Ba to Dy except for Gd in HE 2148–1247 can be accounted for by a mixture of the solar r -pattern and the solar main s -component with $\beta_s(\text{Eu}) \approx 0.14$ corresponding to $\beta_r(\text{Ba}) = 0.077$. This mixture is shown as

the dot-dashed curve in Figure 3b. We cannot offer an explanation for the offset of the Gd data from the dot-dashed curve. For the mixture represented by this curve, both $\beta_r(\text{Ba})$ and $\beta_s(\text{Eu})$ greatly exceed the reference value of $(\text{Ba}/\text{Eu})_{\odot,r}/(\text{Ba}/\text{Eu})_{\odot,s} \approx 0.014$. Consequently, the presence of both the r -process and the s -process contributions in HE 2148–1247 can be established based on the observed Ba/Eu ratio alone.

As the dominant s -process sources in the Galaxy are long-lived low-mass stars, the s -process contributions to the ISM are insignificant at low metallicities corresponding to very early times. As mentioned earlier, it was well recognized that the high enrichments of s -process elements in metal-poor stars are associated with mass transfer from their previous AGB companions in binaries. It was thought that all the stars with high s -process enrichments should have a white dwarf companion now. Some such stars indeed show shifts in their radial velocity (Aoki et al. 2000; Preston & Sneden 2001; Lucatello et al. 2003). However, Preston & Sneden (2001) showed that these cases are not common and a number of highly s -process enriched stars appear to be single stars. According to the above discussion of the AIC events, the highly s -process enriched metal-poor stars, if in binaries, may have neutron stars instead of white dwarfs as companions. Further, the neutron star formed from the AIC of a white dwarf may receive a large kick from, e.g., asymmetric neutrino emission (e.g., Lai & Qian 1998). This would disrupt the binary and may explain the observed single stars with high s -process enrichments. The binary disruption scenario would also imply the existence of highly r -process enriched single stars as significant s -processing might not occur in some AGB companions (see footnote 4).

5. Discussion and Conclusions

The data on metal-poor stars require that the production of the heavy r -nuclei be decoupled from the production of the elements from Na to Zn (including the “ α -elements” and the Fe group). This appears to exclude SNe II with progenitors of $M > 10 M_{\odot}$, or more generally any SNe with extended shell structure, from being the source for the heavy r -nuclei. Considering that the heavy r -nuclei are produced in the neutrino-driven wind from a new-born neutron star, we have argued that only SNe II from stars with $M \sim 8\text{--}10 M_{\odot}$ and AIC events in binary systems, which produce essentially bare neutron stars, satisfy the observational requirement. While neutron star mergers may also satisfy this requirement, they are not considered here as a major source for the heavy r -nuclei. This is because the rarity of neutron star mergers requires very large yields per event, which appear to be in conflict with the observed level of r -process enrichments in metal-poor stars. Further, neutron star mergers cannot produce an intrinsic coupling between r -process and s -process

enrichments in binary systems. As argued above, the AIC events may naturally lead to contamination of the low-mass binary companions’ surface with both *s*-process and *r*-process products. The *s*-process contamination is associated with the AGB progenitor for the white dwarf which subsequently undergoes AIC into a neutron star. Depending on the distribution of the ratio of neutrons to the Fe seeds that results from the evolution of the AGB progenitor, the surface composition of the low-mass binary companion can range from predominantly *r*-process to predominantly *s*-process in origin. The discovery of a highly-enriched mixture of *s*-process and *r*-process elements including possibly Th in HE 2148–1247 provides strong support for the AIC model for the production of the heavy *r*-nuclei. In general, as the binary might be disrupted during an AIC event, this might explain the existence of single stars with high *s*-process enrichments. The binary disruption scenario would also imply the existence of highly *r*-process enriched single stars as significant *s*-processing might not occur in some AGB companions (see footnote 4). Subsequent to the disruption of the binary, the highly *s*-process or *r*-process enriched stars may acquire rather large proper motion.

The AIC model can be tested by discovering (1) more metal-poor stars with high enrichments of both *s*-process and *r*-process elements including Ir, Th, and U, (2) neutron star companions of such stars, and (3) large proper motion of such stars in single configuration. As some light *r*-elements are produced along with the heavy ones in lesser quantities (Qian & Wasserburg 2001b), the detection of the light *r*-elements such as Ag may help the identification of *r*-process enrichments in a star. The AIC events have no optical display due to the lack of an envelope. Direct observations of these events must rely on the detection of neutrinos from the neutron star formed in such events. Gamma rays from decay of the progenitors of the heavy *r*-nuclei, as well as radio signals from the shocked ejecta and the neutron star, may also be observable from an AIC event.

There are several questions regarding the generality of the sources for the heavy *r*-nuclei that are proposed here based on observations of metal-poor stars. It is not evident that all the heavy *r*-nuclei in the Galaxy were produced by low-mass ($\sim 8\text{--}10 M_{\odot}$) SNe II and AIC events. The mass range of $\sim 8\text{--}10 M_{\odot}$ corresponds to only $\sim 28\%$ of all the stars with $M \sim 8\text{--}60 M_{\odot}$ for a Salpeter initial mass function (IMF) of the form $dN/dM \propto M^{-2.35}$. For the low-mass SNe II to constitute $\sim 50\%$ of all SNe II would require a drastic change from -2.35 to -4.11 in the exponent of the IMF. Thus, low-mass SNe II are perhaps not the major source for the heavy *r*-nuclei due to the narrow mass range. If the proposed AIC model is not responsible for the bulk of the heavy *r*-nuclei, either, then the question is — what are the major sources for these nuclei? If the AIC events are the dominant or sole source for the heavy *r*-nuclei, then it is necessary to provide a detailed description of the *r*-process production and the chemical enrichment associated with this scenario.

First consider the issue of chemical enrichment. In our earlier model (Wasserburg & Qian 2000; Qian & Wasserburg 2001b, 2002), we attributed the heavy r -nuclei to $\sim 90\%$ of SNe II [SNe II(H)] and the bulk of the light r -nuclei to the rest [SNe II(L)]. In addition, it was required that SNe II(L) but not SNe II(H) produce the elements from Na to Zn (including Fe). For the model proposed here with AIC events being the major source for the heavy r -nuclei, there is no need to require that most SNe II produce no elements from Na to Zn. Thus, all SNe II from stars with $M > 10 M_\odot$ could be SNe II(L). This removes the conflict between our earlier model and observations of SN II light curves, which showed that most SNe II produce $\sim 0.1 M_\odot$ of Fe (e.g., Table 1 in Sollerman 2002). With this Fe yield and a Galactic SN II rate of $\sim (30 \text{ yr})^{-1}$, $\sim 3 \times 10^8$ SNe II over the Galactic history of $\sim 10^{10}$ yr would enrich the total baryonic mass of $\sim 10^{11} M_\odot$ in the Galaxy with $\sim 1/3$ of the solar Fe mass fraction ($\approx 10^{-3}$). This is in accord with the expected additional Fe contributions from SNe Ia.

As in the case of SNe II, the amount of ISM which will dilute the nucleosynthetic products is determined by the total energy injected into the ISM. The energy injected by an AIC event is perhaps comparable to that by an SN II (Woosley & Baron 1992), which corresponds to a standard dilution mass of $\sim 3 \times 10^4 M_\odot$ (e.g., Thornton et al. 1998). If $n_\odot \sim 10^3$ AIC events provided this dilution mass with the solar abundances of the heavy r -nuclei (see §2), then a total of $\sim 3 \times 10^9$ AIC events must have occurred to provide the same enrichment to the total baryonic mass of $\sim 10^{11} M_\odot$ in the Galaxy. This is ~ 10 times more than the total number of SNe II over the Galactic history, and therefore, suggests that the Galactic rate of AIC events must be $\sim (3 \text{ yr})^{-1}$ if these events are the major source for the heavy r -nuclei. The value of $n_\odot \sim 10^3$ used to obtain this rate corresponds to a frequency of $\sim (10^7 \text{ yr})^{-1}$ for replenishment of the heavy r -nuclei in the standard dilution mass. This frequency was inferred from the original measurements of the $^{182}\text{W}/^{183}\text{W}$ deficiencies in iron meteorites relative to the earth's crust, which imply $(^{182}\text{Hf}/^{180}\text{Hf})_{\text{ESS}} = 2.8 \times 10^{-4}$ in the early solar system. Recent measurements by Yin et al. (2002) and Kleine et al. (2002) give $(^{182}\text{Hf}/^{180}\text{Hf})_{\text{ESS}} = 10^{-4}$. Repeating the argument of Wasserburg et al. (1996) for this new value indicates that the frequency for replenishment of the heavy r -nuclei should be reduced by a factor of ~ 2 , and therefore, the required Galactic rate for AIC events to be the major source for the heavy r -nuclei is $\sim (6 \text{ yr})^{-1}$.

If the Galactic rate of AIC events is indeed $\sim (6 \text{ yr})^{-1}$, then the neutrino signals from such an event will be observed in the near future by detectors such as Super Kamiokande (SK). The neutrino signals from an AIC event should be similar to those from an SN II. The dominant signals in a water Čerenkov detector such as SK are caused by $\bar{\nu}_e + p \rightarrow n + e^+$. Eleven $\bar{\nu}_e$ events were observed from SN 1987A at a distance of 50 kpc by the Kamiokande II water detector with a fiducial mass of 2.14 kton (Hirata et al. 1987). Thus, if an AIC

event occurs at a distance of 10 kpc, $\sim 11(50 \text{ kpc}/10 \text{ kpc})^2(32 \text{ kton}/2.14 \text{ kton}) \sim 4000 \bar{\nu}_e$ events will be observed by SK with a fiducial mass of 32 kton.

The AIC events were originally proposed to explain the formation of low-mass X-ray binaries (LMXBs), which consist of a low-mass star and a neutron star (see Canal et al. 1990 for a review). However, we cannot connect the AIC events with LMXBs based on the required Galactic rate for these events to be the major source for the heavy r -nuclei. There are ≈ 120 LMXBs observed in the Galaxy (van Paradijs 1995). If the lifetime of an LMXB is $\sim 10^8$ – 10^9 yr, the birth rate of LMXBs is $\sim (10^6$ – $10^7 \text{ yr})^{-1}$ (Verbunt & van den Heuvel 1995). This is far below the Galactic rate of SNe II and that of AIC events discussed above. Therefore, if the AIC events are the major source for the heavy r -nuclei, these events may have little to do with the formation of LMXBs. We note that the observed LMXBs have very short orbital periods of ~ 0.2 – 400 hr (White, Nagase, & Parmar 1995) while the binary systems containing low-mass stars with high s -process enrichments tend to have much longer orbital periods⁵ of > 1 yr (Aoki et al. 2000; Preston & Sneden 2001; Cohen et al. 2003). It is plausible that the AIC events frequently occur in wide binary systems while LMXBs are the rare outcome of the evolution of close binary systems.

The Galactic birth rate of pulsars, which are rotating neutron stars with high magnetic fields, was estimated to be $(60$ – $330 \text{ yr})^{-1}$ (Lyne et al. 1998). It is conventional to consider all pulsars as the products of SNe II. As only $\sim 10\%$ of the catalogued SN II remnants in the Galaxy are observed to contain pulsars (Kaspi & Helfand 2002), the Galactic SN II rate of $\sim (30 \text{ yr})^{-1}$ is only consistent with the lower end of the estimated pulsar birth rate. If AIC events are the major source for the heavy r -nuclei, the required Galactic rate of $\sim (6 \text{ yr})^{-1}$ for these events could easily accommodate the higher end of the estimated pulsar birth rate. In addition, accretion onto the white dwarf in an AIC event would provide a natural mechanism to produce a rapidly rotating neutron star, which is required for the pulsar mechanism.

According to the above discussion, if AIC events are the major source for the heavy r -nuclei, their occurrences in the Galaxy must have produced $\sim (10^{10} \text{ yr})/(6 \text{ yr}) \sim 1.6 \times 10^9$ neutron stars, which are ~ 5 times more than those produced by SNe II. This implies that AIC events are a frequent outcome of binary evolution, far more common than SNe Ia. On the other hand, progenitor systems of AIC events only constitute a fraction of all binary systems, most of which would evolve into white dwarf binaries. Thus, the total number of white dwarf binaries must greatly exceed $\sim 1.6 \times 10^9$, which is the number of neutron stars produced by AIC events. These white dwarf binaries could contribute significantly to the

⁵An exception is the system containing HE 0024–2523 with an orbital period of 3.14 days.

inventory of MACHOs.

As discussed in §4, AIC events would lead to high s -process and high r -process enrichments in binary systems. These enrichments are not diagnostic of the composition of the ISM from which the binary systems were formed. There are three distinct times involved here, which correspond to the formation of the binary, the development of the AGB phase, and the AIC event. We note that there may be significant delays between the first and the other two times depending on the stellar masses. Due to the time ($\gtrsim 10^9$ yr) required for the evolution of the most abundant stars ($M < 2 M_\odot$) to reach the AGB phase, it is plausible that there were no significant s -process contributions to the ISM at low $[\text{Fe}/\text{H}]$. Prior to the onset of SN Ia contributions at $[\text{Fe}/\text{H}] \sim -1$, the elements from Na to Zn can only be produced by stars with $M > 10 M_\odot$. We consider these elements instead of the heavy r -elements or the s -process elements as more reliable monitors of the ISM because surface contamination is not likely an issue in interpreting the stellar data on these elements. Consequently, the abundances of the elements from Na to Zn can be plausibly associated with ongoing “average” evolution of the ISM at $-3 < [\text{Fe}/\text{H}] < -1$.

As we have emphasized here the role of binary systems at low $[\text{Fe}/\text{H}]$, we must consider the effects of SNe Ia, which produce dominantly the Fe group elements but not the “ α -elements.” The observed transition in the trend for evolution of Mg, Si, Ca, and Ti relative to Fe at $[\text{Fe}/\text{H}] \sim -1$ indicates that major Fe contributions from SNe Ia only occur at $[\text{Fe}/\text{H}] \gtrsim -1$. The role of the AIC events as the major source for the heavy r -nuclei especially at $[\text{Fe}/\text{H}] < -1$ then implies severe restrictions on binary evolution. It is possible that SNe Ia may only occur through the merging of two white dwarfs, which are produced in binary systems with two low-mass stars (e.g., Iben 1985). In this case, the onset of SN Ia contributions would require a delay of $\sim 10^9$ yr similar to that for the onset of major s -process contributions to the ISM. The parameter space for the mass and the accretion rate of a C-O or O-Ne-Mg white dwarf leading to AIC or an SN Ia was studied by Nomoto & Kondo (1991). More studies of this kind and of binary evolution in general are much needed to assess the possibility of the predominance of AIC events over SNe Ia at $[\text{Fe}/\text{H}] < -1$.

Another crucial issue to be addressed is the r -process production by AIC events. The diverse nature of the r -process was inferred from the meteoritic data on ^{182}Hf and ^{129}I by Wasserburg et al. (1996). This was supported by observations of metal-poor stars, which showed that the light r -elements such as Rh and Ag in CS 22892–052 (Snedden et al. 2000) and CS 31082–001 (Hill et al. 2002) are deficient relative to the solar r -pattern translated to pass through the Eu data (see also Cowan et al. 2002; Johnson & Bolte 2002b). So far ab initio approaches are unable to define the r -process yield patterns. Observations (Snedden et al. 1996; Westin et al. 2000; Johnson & Bolte 2001) showed that the heavy r -elements

in a number of metal-poor stars closely follow the solar r -pattern. This comparison between the pattern resulting from a very small number of r -process events (only a single event in some cases) at low $[\text{Fe}/\text{H}]$ and the solar r -pattern resulting from many events indicates that the production of the heavy r -nuclei is well behaved and not very sensitive to the individual production site. One possible means of obtaining uniform yield patterns for the heavy r -nuclei would be fission cycling, which tends to produce a robust pattern with two peaks at $A \sim 130$ and 195 , respectively (e.g., Freiburghaus et al. 1999). The observational data do not require an invariant yield pattern of the heavy r -nuclei. For example, the Th/Eu ratio in CS 22892-052 differs from that in CS 31082-001 by an amount that is too large to be explained by the possible age difference between the two stars (Qian 2002). However, if Th is produced but if fission cycling does not occur, the initial ratio of neutrons to the seed nuclei for the r -process is still rather restricted. This limits but does not fix the resulting yield pattern. It may be possible to obtain a regular but not fixed pattern for the heavy r -nuclei including Th without fission cycling (e.g., Qian 2002).

The basic physics of neutron star formation and neutrino emission is essentially the same for both SNe II and AIC events. Neither process is sufficiently understood to provide a reliable prediction for r -process nucleosynthesis. It is hoped that a focused effort on AIC models might be fruitful in exploring the problem of r -process nucleosynthesis without consideration of the complexity of SN II dynamics. The neutrino-driven wind associated with AIC events requires further studies. Among the important physics issues, effects of neutrino flavor mixing (e.g., Caldwell, Fuller, & Qian 2000) and neutron star magnetic field on the conditions in the wind deserve special attention.

In conclusion, we consider that a strong and coherent case can be made for the production of the heavy r -nuclei by AIC events in binary systems based on observations of metal-poor stars with $[\text{Fe}/\text{H}] \sim -3$. More specifically, the production of the heavy r -nuclei occurs in the neutrino-driven wind from the neutron star produced by the AIC of a white dwarf in a binary system. This scenario provides a coupling between the r -process and the s -process as the progenitor for the white dwarf may produce s -process elements during the AGB phase. Whether this scenario with AIC may also be the dominant source for the heavy r -nuclei in the Galaxy remains to be investigated. With regard to our earlier model, the assignment of heavy r -element production to SNe II(H) must be changed to the AIC events. The requirement of a major change in the mode of star formation at $[\text{Fe}/\text{H}] \sim -3$ and the decoupling of the production of the heavy r -nuclei from that of Fe appear to be firm. Prior to $[\text{Fe}/\text{H}] \sim -3$ being obtained in the ISM, VMSs with very large dilution masses played a dominant role in chemical evolution. The VMS activities ceased and major formation of normal stars took over at $[\text{Fe}/\text{H}] \sim -3$. The evolution of neutron-capture elements at $-3 \lesssim [\text{Fe}/\text{H}] < -1$ must be reinvestigated now that some coupling between the r -process and

the s -process has been established. In particular, our previous assumption of no significant s -process contributions at $[\text{Fe}/\text{H}] < -1$ and our inferred modifications of the s -process and the r -process components of the solar abundances must be reevaluated.

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A. Chemical Evolution Model

Equation (1) can be derived from a simple model that treats the evolution of the abundance of element E in the ISM. Consider a parcel of matter initially consisting of gas only. We assume that the gas of the parcel is well mixed and its amount can only decrease at subsequent times due to astration or escape from the parcel. At time t , the total numbers of E and hydrogen atoms in the gas of the parcel are (E) and (H) , respectively. The evolution of (E) is governed by

$$\frac{d(\text{E})}{dt} = \sum_i P_i(\text{E}) + \left(\frac{\text{E}}{\text{H}}\right) \frac{d(\text{H})}{dt}, \quad (\text{A1})$$

where $P_i(\text{E})$ is the number of E atoms injected into the gas per unit time from prototypical sources of type i , and $d(\text{H})/dt < 0$ represents the total rate of loss of gas due to astration and escape from the parcel. Equation (A1) can be rewritten as

$$\frac{d(\text{E}/\text{H})}{dt} = \sum_i \frac{P_i(\text{E})}{(\text{H})} = \sum_i \frac{Y_i(\text{E})}{\text{H}} \frac{dn_i}{dt}, \quad (\text{A2})$$

where the yield $Y_i(\text{E})/\text{H}$ is the number of E atoms produced by a single event of type i per H atom in a standard reference mass of gas which will mix with the nucleosynthetic products from such an event. This yield is assumed to be the same for all such events. In equation (A2), n_i is the number of the events of type i that have occurred in the standard reference mass of gas up to time t . Equation (A2) can be solved to give

$$\left(\frac{\text{E}}{\text{H}}\right) = \left(\frac{\text{E}}{\text{H}}\right)_P + \sum_i \frac{Y_i(\text{E})}{\text{H}} n_i, \quad (\text{A3})$$

where $(\text{E}/\text{H})_P$ is the initial value and corresponds to the prompt inventory of E that exists in the gas before normal astration takes place. Equation (1) is obtained for a single type of source when the prompt inventory is overwhelmed by the subsequent production.

If two parcels of matter with different evolutionary histories are mixed, then the equation for (E/H) is of the same form as in equation (A3) but n_i becomes the weighted value \tilde{n}_i for the mixture. If matter with no enrichment is mixed with an ISM that has been enriched in E, then both the resultant \tilde{n}_i and (E/H) are decreased. It is not possible to decrease \tilde{n}_i and keep (E/H) fixed. The abundance patterns resulting from mixed or unmixed parcels is unchanged as long as the yield pattern of each type and the ratios n_i/n_j for all contributing types are fixed. See Qian & Wasserburg (2001b) for a full treatment.

If we consider infall of unenriched gas during the evolution of a parcel, then the term $d(H)/dt$ in equation (A1) is replaced by $d(H)/dt - d(H)_{\text{in}}/dt$ with $d(H)_{\text{in}}/dt$ being the rate of infall. This gives

$$\frac{d(E/H)}{dt} = \sum_i \frac{Y_i(E)}{H} \frac{dn_i}{dt} - \left(\frac{E}{H}\right) \frac{1}{(H)} \frac{d(H)_{\text{in}}}{dt}. \quad (\text{A4})$$

The solution to equation (A4) depends in detail on the rate of infall and can be formally written as

$$\left(\frac{E}{H}\right) = \left(\frac{E}{H}\right)_P + \sum_i \frac{Y_i(E)}{H} n_i - \int_0^t \left(\frac{E}{H}\right) \frac{1}{(H)} \frac{d(H)_{\text{in}}}{dt'} dt'. \quad (\text{A5})$$

Compared with the case without infall, equation (A5) gives a lower value of (E/H) for a given n_i or requires larger values of n_i for a fixed (E/H) . However, the ratio of the n_i values corresponding to two different values of (E/H) may not be significantly affected by infall. The argument presented in the text below equation (1) is based on the ratio n/n_\odot , and therefore, is not substantially altered. The basic problem discussed there has to do with the observations that different metal-poor stars with essentially the same $[\text{Fe}/H]$ have widely varying inventories of heavy r -nuclei. In some cases, the observed abundances of these nuclei are so high that they cannot be attributed to enrichments of the ISM from which the stars were formed but must have resulted from surface contamination in binary systems.

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Fig. 1.— (a) Data on $\log \epsilon(\text{Eu})$ versus $[\text{Fe}/\text{H}]$ for metal-poor stars (filled squares: McWilliam et al. 1995; open circles: Burris et al. 2000; open triangles: Westin et al. 2000; filled diamond: Sneden et al. 2000; asterisks: Johnson 2002; filled circle: Hill et al. 2002; filled triangle: Cowan et al. 2002; open diamond: Cohen et al. 2003). The dotted line indicates $\log \epsilon_{\odot}(\text{Eu})$ in the sun. The solid line segment of unit slope indicates the mean trend for evolution of Eu relative to Fe at $-2.4 < [\text{Fe}/\text{H}] < -1$. A line of unit slope corresponds to additions of Eu and Fe to the big bang debris at a constant production ratio. Note the large scatter and the abrupt departure from the dashed extension of the solid line segment in the region of $-3 < [\text{Fe}/\text{H}] < -2.4$ between the two vertical dashed lines. The open diamond represents the data on HE 2148–1247 (Cohen et al. 2003) and clearly lies far above the trend. (b) Data on $\log \epsilon(\text{Ba})$ versus $[\text{Fe}/\text{H}]$ for metal-poor stars. Data symbols are the same as in (a) except that the filled squares now represent the data from McWilliam (1998) and the asterisks now represent the data from Ryan et al. (1996) and Norris et al. (2001). The dotted line indicates $\log \epsilon_{\odot}(\text{Ba})$ in the sun. The solid and dot-dashed curves indicate the mean trend for evolution of Ba relative to Fe at $-4 < [\text{Fe}/\text{H}] < -1$. These two curves correspond to increases by factors of 10 (solid curve) and 20 (dot-dashed curve) in the relative production of Ba with respect to Fe at $[\text{Fe}/\text{H}] = -3$. The dashed line of unit slope indicates the mean trend for evolution of Ba relative to Fe at $-2.4 < [\text{Fe}/\text{H}] < -1$ and is far above the data at $-4 < [\text{Fe}/\text{H}] < -3$. Note again the large scatter in the region of $-3 < [\text{Fe}/\text{H}] < -2.4$ between the two vertical dashed lines. The open diamond for the data on HE 2148–1247 (Cohen et al. 2003) clearly lies far above the trend.

Fig. 2.— Data on the elements from C to Pt in HD 115444 (filled circles), HD 122563 (squares: Westin et al. 2000), and CS 31082-001 (asterisks: Hill et al. 2002) with $[\text{Fe}/\text{H}] = -2.99, -2.74$, and -2.9 , respectively. (a) The $\log \epsilon$ values for the elements from C to Ge are shown. The data on CS 31082-001 are connected with solid line segments as a guide. Missing segments mean incomplete data. The downward arrow at the asterisk for N indicates an upper limit. Note that the $\log \epsilon$ values for the elements from Na to Zn are almost indistinguishable for the three stars. (b) The $\log \epsilon$ values for the elements from Sr to Pt are shown. The data on CS 31082-001 to the left of the vertical dotted line are again connected with solid line segments as a guide. In the region to the right of the vertical dotted line, the solid, dot-dashed, and dashed curves are the solar r -pattern translated to pass through the Eu data for CS 31082-001, HD 115444, and HD 122563, respectively. Note the close description of the data by these curves. The shift between the solid and the dashed curves is ~ 2 dex.

Fig. 3.— (a) Comparison of blind predictions (filled circles connected with solid curves) from the phenomenological model of Qian & Wasserburg (2001b, 2002) with the data (squares with error bars) on HE 2148–1247 (Cohen et al. 2003). The predictions were made from the

preliminary values of $\log \epsilon(\text{Fe}) = 5.16$ and $\log \epsilon(\text{Eu}) = 0.34$, which are close to the data on Fe and Eu from the final analyses. Note the close agreement between the predictions and the data for the elements from Mg to Ni and for Sr, Y, and Zr. Also note the large discrepancy for the elements from Ba to Nd. No predictions were made for C, N, and Pb. The downward arrow at the data symbol for Th indicates only a possible detection. (b) The data on the elements from Ba to Dy are compared with the solar r -pattern (thin solid curve) and the solar main s -component (dotted curve), both of which are translated to pass through the Eu data. The predictions in (a) are close to the translated solar r -pattern and not shown. It is clear that the data must represent a mixture of the solar r -pattern and the solar main s -component. The dot-dashed curve is such a mixture with 14% of the Eu contributed by the s -process [$\beta_s(\text{Eu}) = 0.14$] and describes the data very well except for Gd.

Fig. 4.— (a) Comparison of mixtures having a fixed number of Ba atoms with different proportions from the r -process and the s -process: pure s -process represented by the solar main s -component [dashed curve, $\beta_r(\text{Ba}) = 0$], pure r -process represented by the solar r -pattern [thick solid curve, $\beta_r(\text{Ba}) = 1$], and a mixture with equal contributions to Ba from the r -process and the s -process [dot-dashed curve, $\beta_r(\text{Ba}) = 0.5$]. Note that the dot-dashed curve closely follows the solar r -pattern. (b) Same as (a) but the number of Eu atoms is fixed instead with different proportions from the r -process and the s -process: pure s -process [dashed curve, $\beta_s(\text{Eu}) = 1$], pure r -process [thick solid curve, $\beta_s(\text{Eu}) = 0$], and a mixture with equal contributions to Eu from the r -process and the s -process [thin solid curve, $\beta_s(\text{Eu}) = 0.5$]. Note that the thin solid curve closely follow the solar main s -component except for the element Ir. The dot-dashed curve for the mixture in (a) with 50% of the Ba from the r -process is also shown in (b). This mixture corresponds to only $\approx 1.4\%$ of the Eu being contributed from the s -process [$\beta_s(\text{Eu}) = 0.014$], and therefore, stays close to the solar r -pattern.















